MOCHA - Multi-Study Ocean Acoustics Human Effects Analysis

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LONG-TERM GOALS

The long-term goal is to substantially enhance our quantitative understanding of the response of marine mammals to navy sonar and other acoustic stimuli, by maximizing the information gain from Behavioral Response Studies (BRSs). We aim to develop and implement innovative methods for the analysis of BRS data, and to complement and enhance analyses already taking place as part of each current Navy-funded BRS project. We aim for synergies by looking at the studies in combination.

OBJECTIVES

The overall objective of this project has been to develop and implement innovative statistical methodologies for the analysis of behavioral response study data. Our focus has been on studies estimating the response to mid-frequency active sonar, but the methods developed will be widely applicable. We aim to maximize the inferences that can be drawn from current and ongoing studies as well as to provide advice on future studies. Advances have been made in close collaboration with those involved in existing BRS projects, using a working group format. This approach has enabled us to complement and enhance the analytical work already being undertaken, as well as to be flexible and incorporate new ideas as they have arisen in working group sessions.

The project has four specific objectives:

1. Improve methods for combining diverse behavioral measures into metrics of behavioral response. Consideration is given to obtaining metrics that can be linked to biological consequences.
2. Improve methods for estimating dose-response functions for individual studies. This involves both developing and applying cutting-edge statistical methods, as well as considering which contextual variables in addition to acoustic dose can be incorporated into the analysis. The output is improved estimates of response curves (with uncertainty) for each study.
3. Combine information across studies and species ("meta-analysis"), making use of expert biological opinion, to make predictions about taxa and contexts not yet studied. Differences in methods/protocols between studies are accounted for.

4. Based on the above, determine where major uncertainties still lie (for example, through sensitivity analyses), and hence suggest where future experimental effort might be applied most fruitfully.

APPROACH

We formed a working group, supported by two full-time post-doctoral researchers (Stacy DeRuiter and Dina Sadykova), to develop and implement innovative methods for the analysis of the results from BRSs. The working group is composed of the chief scientists of existing BRS projects (Sirena sonar trials on sperm whales, Bahamas BRS, SOCAL BRS, Norwegian 3S and 3S2, Duke University Cape Hatteras EK60 experiments and Cape Hatteras/SOCAL BRS), together with other scientists working on BRS issues and statisticians who have expertise in the analysis of biological data of this kind. A smaller steering committee, comprising the PIs on this project and the BRS PIs, has provided overall direction.

Over the course of the project we have held a series of workshops attended by the working group, steering group and project post-doctoral researchers. Each workshop has focussed on a functional/taxonomic group of marine mammals (deep divers, other odontocetes, pilot whales and baleen whales). We began with deep divers (beaked whales and sperm whales) because this group contains species of concern, there are data for these species across multiple BRS projects, the metrics measured are fairly well defined, and the social complexities are minimized. We then increased social complexity by looking at other odontocetes (killer whales, Risso's dolphins, false killer whale, melon-headed whale) followed by pilot whales for which there are data from most BRSs. The 5th workshop focussed on baleen whales. The final workshop was held in December 2014; this was an open workshop aimed at disseminating findings as well as soliciting feedback and external peer-review.

DeRuiter and Sadykova have conducted the majority of the research and model development over the course of the project under the supervision of Harris and Thomas, with frequent inputs from other project partners as required. Additional post-doctoral researchers at CREEM with particular expertise have become involved in the latter stages of the project.

WORK COMPLETED

The final working group meeting took place within the last fiscal year, and was hosted by the University of St Andrews, St Andrews, UK in December 2014. MOCHA personnel presented an overview of the methods development and analyses that had been carried out to that point. We invited some external participants to this final meeting which provided an opportunity for feedback and external peer-review. The reports of all working group meetings can be found at http://www.creem.st-and.ac.uk/mocha/project-outputs.

Over the last year we have continued our method development for deep divers, odontocetes and baleen whales and have made progress on methods appropriate for meta-analysis across species and projects. We have now completed 27 working documents, outlining analysis methods pertaining to a range of species from each group. Many of these have accompanying code in the open-source statistical software R (R Core Team 2015), as well as guidelines for applying the methodologies to other datasets. The working documents and R code files are available to the working group as well as all BRS project personnel. In addition, within the last year we have co-authored 8 publications in peer-reviewed journals (see Publications below).

We have conducted a number of univariate analyses, which have primarily relied on the use of generalized estimating equations (GEEs) (Hardin and Hilbe, 2003). GEE methods have allowed us to explore changes in key parameters in before-during-after phases of sound exposure as well as characterize some aspects of baseline behavior. This has resulted in three publications to date with others in preparation. More recently we have been exploring the use of these models for meta-analysis. Some of the methods developed to detect change-points in an individual's behavior in the presence of sound exposure have also been applied by project teams, such as the application of the Mahalanobis distance change-point method to data from a controlled exposure experiment (CEE) conducted on a Baird's beaked whale (Stimpert et al. 2015) and northern bottlenose whale (Miller et al. 2015). Other examples are currently being prepared for submission (e.g., minke whale, blue whale). We are preparing a manuscript which compares variants of the application of Mahalanobis distance techniques using simulated DTAG data, which will provide guidance to the community on the application of this method.

We have also made further progress in the application of process-based time series models such as hidden Markov models (HMMs) and other latent-state models to BRS data. We focus on the development of these models in the Results section. However, in terms of work completed we have seven manuscripts that are currently being prepared for submission, one on blue whales, one on sperm whales and a further five on pilot whales.

We have conducted a number of dose-response analyses using two different methods – a Bayesian hierarchical model and a Cox proportional hazards model. The focus over this year has been to use the Bayesian hierarchical model for meta-analysis across species. The results of this effort were presented and discussed at the final working group meeting and manuscript preparation is planned for the next fiscal year. The Cox proportional hazards model has been used in a recurrent event survival analysis framework to produce dose-response severity functions for a number of species. This has resulted in two publications (Harris et al. in press, Sivle et al. in press) and another is being prepared.

As well as leading on some research avenues, we have also provided support to the individual BRS projects when requested. This has led to a number of collaborative publications (see Publications below), with more in the preparation stage.

RESULTS

In previous years we have reported on findings from the application of a Mahalanobis change-point detection method (DeRuiter et al. 2013) and on the application of a Bayesian hierarchical dose-response model (Antunes et al. 2014, Miller et al. 2014). The range of methodologies that have been developed and worked on during this fiscal year are described broadly in the Work Completed section. Here we will describe the development and application of HMMs, as these have been a focus in the latter part of the project.

HMMs are proving to be a useful tool in the BRS analysis toolkit as the deployment of animal-borne sensors is resulting in an increasing amount of complex multivariate time-series data being collected on a small number of individual animals. These models allow multiple metrics to be combined into one analysis, but they also explicitly acknowledge the time-series nature of the data, and provide an opportunity to explore behavioral states and the probability of transitioning between these states as a function of sound exposure. We have developed a suite of HMM model variants and generic code for their application to BRS data. These include methods for integrating data of differing resolutions from

multiple data streams, dealing with missing data and a formulation that includes a computationally efficient discrete random effect to account for the differences between animals. The method allows for effects of acoustic disturbance on both the between-state transition probabilities (e.g., decreased probability of foraging) and the state-dependent parameters (e.g., decrease in sound production during foraging).

We demonstrate the applicability of these models using two examples:

HMMs were used to quantify baseline behavior of 22 long-finned pilot whales tagged as part of the 3S and 3S2 projects. The dataset combines acoustic, movement and visual tracking data collected at different temporal resolutions and with missing values. Not all of the 22 tag records had concurrent acoustic or visual data (8 and 12 records, respectively). In these instances the HMM estimated the most likely behavior state based upon the available data alone while pooling information about the state-dependent distributions across the tag records. A two-step analysis allowed us to identify dives from breathing intervals, and further classify the dives into foraging, fast breathing, travelling and "common" dives (Figure 1).

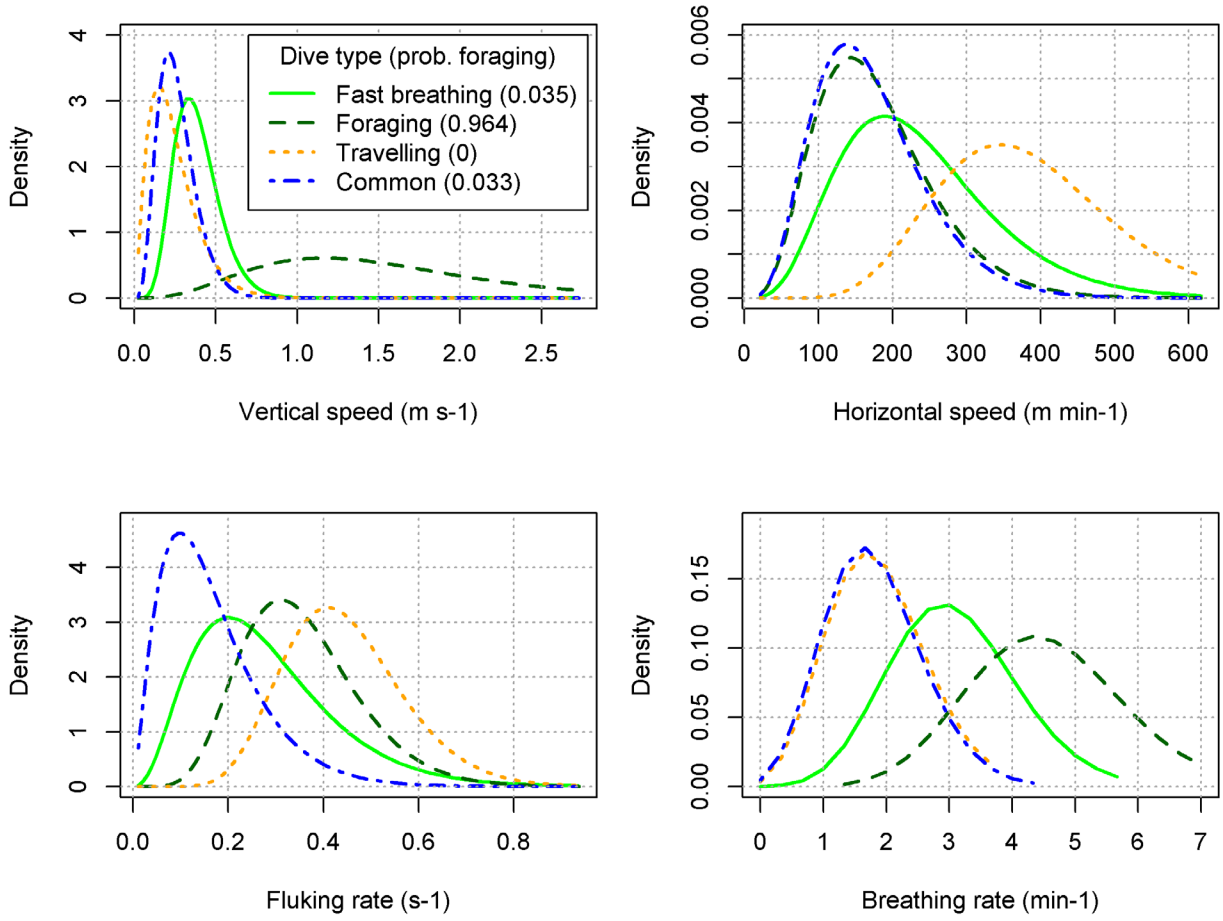

Figure 1: HMM analysis of pilot whale dives. The HMM was specified with state-dependent distributions that aimed to reflect the whales' energetic expenditure (breathing rate), movement effort (fluking rate) and speed of movement both vertically within a dive and horizontally (visual track). Foraging was also informed by the presence of echolocation clicks and variance in pitch, roll and heading.

To describe movement and diving behavior of blue whales tagged as part of the SOCAL project, we fitted an HMM, using the model's hidden states as a proxy for the underlying behavioral state of the animals. The model formulation includes an innovative discrete random effect to account for differences between animals, and also allows for effects of acoustic disturbance on the rates of transition between states. The model allowed us to identify three main blue whale dive types (shallow feeding (state 1), travel (state 2) and deep feeding (state 3)). We also quantified significant differences between whales in probabilities of transition between the dive types (behavioral contexts), and measured how blue whales responded to acoustic disturbance, with a reduction in deep foraging behavior and more shorter, shallower dives (Figure 2).

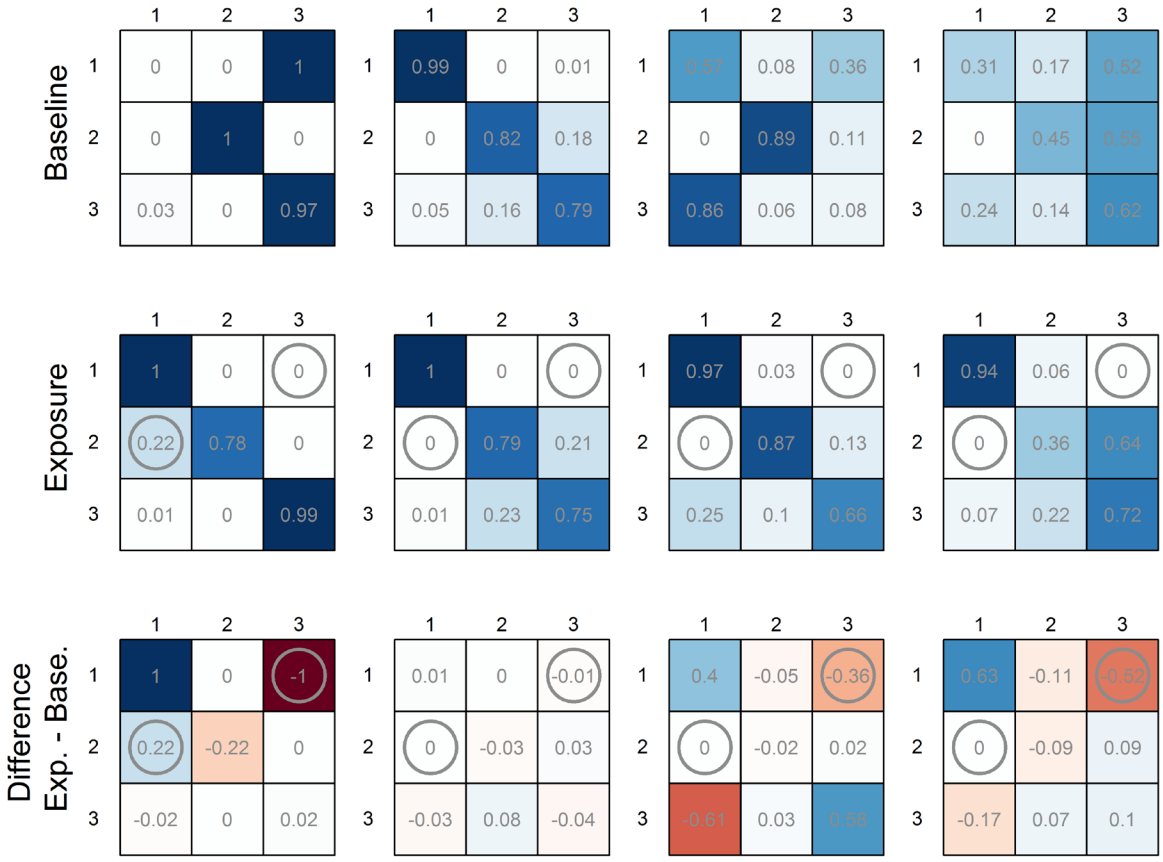

Figure 2: Fitted model estimates of the transition probability matrices (TPM) for the 3-state HMM with 4 behavioral contexts. In each matrix, state 1 most likely represents shallow feeding, state 2 represents travel and state 3 represents deep feeding. The 4 behavioural contexts account for variation in transition probabilities from whale to whale. Characteristics of the TPM for each context are, from left to right, very high persistence in states 2 and 3, and immediate transition from state 1 to 3 (if 1 is ever observed); high persistence in all three states, but with occupancy of state 3 quite; persistence in state 2 and some alternation between states 1-3; and highest probability of switching between states, with frequent transitions to state 3 from other states. For each context, the first row shows the TPM (in the absence of acoustic disturbance), the second row shows the TPM with acoustic disturbance, and the third row shows the difference between the two. The magnitudes of the transition probabilities are indicated by the fill colour, as well as the printed numeric values in each cell. For the TPMs with acoustic disturbance, circles around the probabilities indicate entries corresponding to acoustic-disturbance parameters whose 95% confidence intervals do not contain zero.

IMPACT/APPLICATIONS

This project aims to significantly enhance the Controlled Exposure Experiments component of the Marine Mammals and Biology Program, and it will also address broader commitments of the Navy for environmental compliance. As part of rule making under the US Marine Mammal Protection Act, the Navy has committed to an Integrated Comprehensive Monitoring Program with the following objectives: monitor and assess the effects of Navy activities on protected marine species; ensure that data collected at multiple locations is collected in a manner that allows comparison between and among different geographic locations; assess the efficacy and practicality of the monitoring and mitigation techniques; add to the overall knowledge base of protected marine species and the effects of Navy activities on these species (Stone 2009). As part of its environmental compliance, the Navy must attempt to quantify the effect of sonar operations on marine mammals in all of its operating areas. This requires methods to estimate the relationship between acoustic dosage and other factors with behavioral responses. Here we have been developing frameworks for pooling data across studies and areas to develop more systematic models to quantify these effects.

RELATED PROJECTS

Data being analysed in the MOCHA project comes from a number of BRS projects that have focussed on different geographic areas and species. Below is a list of the projects providing data and links to websites with further information on each project, where available. More information about each project can be found in links listed at http://www.creem.st-and.ac.uk/mocha/links

- Sirena sonar trials on sperm whales
- BRS Bahamas (AUTEC): http://www.nmfs.noaa.gov/pr/acoustics/behavior.htm
- SOCAL BRS: http://sea-inc.net/socal-brs/
- 3S: http://soi.st-andrews.ac.uk/documents/424.pdf
- 3S2: http://www.ffi.no/no/Rapporter/11-01289.pdf
- Cape Hatteras: http://www.serdp.org/Program-Areas/Resource-Conservation-and-Climate-Change/Natural-Resources/Living-Marine-Resources-Ecology-and-Management/RC-2154/RC-2154

Other related research projects are:

- BRREW – This project is providing a review of the status and future of research into behavioral responses of marine mammals to naval sonar exposure.
- LATTE - This three year project is developing and implementing statistical models that integrate passive acoustic monitoring data and animal-borne tag data to estimate the effect of Mid Frequency Active (MFA) sonar on beaked whales at AUTEC.
- M3R program – This is the passive acoustics monitoring algorithms and tools development program at NUWC.
- PCADs – This project aims to operationalize the Population Consequences of Acoustic Disturbance framework, focusing (currently) on four case study species, including beaked whales at AUTEC.

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3rd MOCHA Working Group Meeting Report, 2013. (Technical Report) Available at http://www.creem.st-and.ac.uk/mocha/project-outputs [published]

4th MOCHA Working Group Meeting Report, 2013. (Technical Report) Available at http://www.creem.st-and.ac.uk/mocha/project-outputs [published]

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